

A Large Extension of the CfA Galactic CO Survey

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Abstract. The Galactic CO survey of Dame, Hartmann, & Thaddeus (2001; hereafter DHT) is composed of both large-scale unbiased surveys, mainly concentrated within 10° of the Galactic plane, and targeted observations of clouds at higher latitudes. Analysis of all-sky IRAS and 21 cm maps suggests that the DHT survey is nearly complete for clouds larger than $\sim 1^\circ$, even though roughly half of the total area at $|b| < 30^\circ$ was not observed. In October 2001 we began a new survey of all of this unobserved area that is accessible to the northern 1.2 meter telescope, approximately $6,600 \text{ deg}^2$ between $l = 0^\circ$ and 230° , mainly in the latitude range $|b| = 10^\circ$ – 30° . At least 12 hours per day is being dedicated to this large project, which is sampled every $1/4^\circ$ (every other beamwidth) to an rms sensitivity of 0.19 K at a velocity resolution of 0.65 km s^{-1} . As of May 2003, we have obtained 90,000 of the 106,000 spectra required to complete the survey. While, as expected, the new observations do not substantially change the DHT map, 68 relatively small and isolated molecular clouds at intermediate latitudes have so far been discovered.

The survey has also been extended to $b < -30^\circ$ in two regions, one in the vicinity of the large MBM clouds 53-55 at $l \sim 90^\circ$ and the other south of the Taurus clouds at $l \sim 170^\circ$. Substantial amounts of molecular gas were detected in both of these high-latitude regions.

1. Introduction

The 1.2 meter millimeter-wave telescopes at the Harvard-Smithsonian Center for Astrophysics and at CTIO in Chile have been playing a leading role in surveying the molecular gas in our Galaxy for over two decades. A significant milestone of this project was reached two years ago, with the publication of the composite CO survey of Dame, Hartmann, & Thaddeus (2001; hereafter DHT). The DHT survey has 16 times more spectra than the previous composite survey at $1/2^\circ$ angular resolution done with the same telescopes (Dame et al. 1987), up to 3.4 times higher angular resolution, and up to 10 times higher sensitivity per unit solid angle.

In DHT it was argued that the survey was largely complete at $|b| < 30^\circ$, even though roughly half of that area had not been surveyed. For several years prior to the publication of DHT, we had used the IRAS far-infrared survey as a tracer of total gas, and the Leiden-Dwingeloo 21 cm survey as a tracer of atomic gas, in order to deduce from the differences between the two the existence of molecular

clouds outside the limits of our large Galactic plane surveys; about a dozen clouds were found in this way and subsequently mapped in CO. DHT used the IRAS and Leiden-Dwingeloo 21 cm surveys to show that their molecular survey was nearly complete for clouds brighter in CO than $\sim 1 \text{ K km s}^{-1} \text{ deg}^2$; for a typical high-latitude cloud at a distance of 100 pc, this brightness corresponds to an H_2 mass of only $9 M_\odot$ and an angular size of about 1° . Smaller clouds could slip through the net of the analysis, since it was limited by the $36'$ resolution of the 21 cm survey and by small-scale variations in the dust temperature and gas-to-dust ratio.

Here we describe our efforts over the past three years to fill in all of the DHT survey area accessible to our northern telescope with uniform sampling every $1/4^\circ$. In terms of number of spectra and total integration time, this is by far the largest single survey undertaken with either of the 1.2 m telescopes, requiring up to 18 hours per day for three 7-month observing seasons. In the next section we will describe the observations in detail, then go on to discuss some preliminary results from the survey, which is now about 85% complete.

2. Observations

Our new CO survey includes all of the area at $|b| < 30^\circ$ and $\delta > -17^\circ$ that is not covered by the DHT survey, or covered only by survey No. 1 in that paper, which has an effective angular resolution of only $1/2^\circ$ (Dame et al. 1987); the total survey area is 6600 deg^2 . The survey sensitivity of $0.19 \text{ K in } 0.65 \text{ km s}^{-1}$ spectral channels is typical of our Galactic plane surveys, and is adequate to detect molecular clouds with visual extinctions as low as 0.1 mag. The survey is being conducted by sequentially observing 4 interleaved $1/2^\circ$ grids, for a final sampling interval of $1/4^\circ$ —slightly better than every other beamwidth ($8.4'$). After 3 full observing seasons we have obtained 90,000 of the 106,000 spectra required to complete the survey at $|b| < 30^\circ$. Recently we have also extended the survey to two regions at $b < -30^\circ$, one near the high-latitude cloud complex MBM 53-55, and the other south of the Taurus dark clouds.

The telluric emission line from CO in the mesosphere is potentially a serious source of contamination in the present survey, which is being done with frequency switching every 1 second over 15 MHz— an efficient mode of data acquisition with the liability that it does not chop out a widely distributed telluric line. When mapping a particular region it is often possible, by observing at the right time, to position the telluric line in LSR velocity well away from the celestial CO emission. In the present survey, however, observations are conducted over the whole sky every day, and the emission observed is often weak and at a velocity which is not precisely known in advance. The telluric line removal therefore has to be handled carefully. A model of the telluric line is fit to all spectra taken on a given day, or in some shorter interval if the line intensity varies rapidly, as it sometimes does. We eliminate from the fit any telluric lines which appear to overlap celestial emission. This model is then subtracted from all spectra taken during that time interval, for cancellation of the telluric line to below the noise in individual spectra and to better than 2% on average. (A useful byproduct of the present survey is high signal-to-noise daily monitoring of the telluric line parameters over three years. Besides well-known seasonal variations,

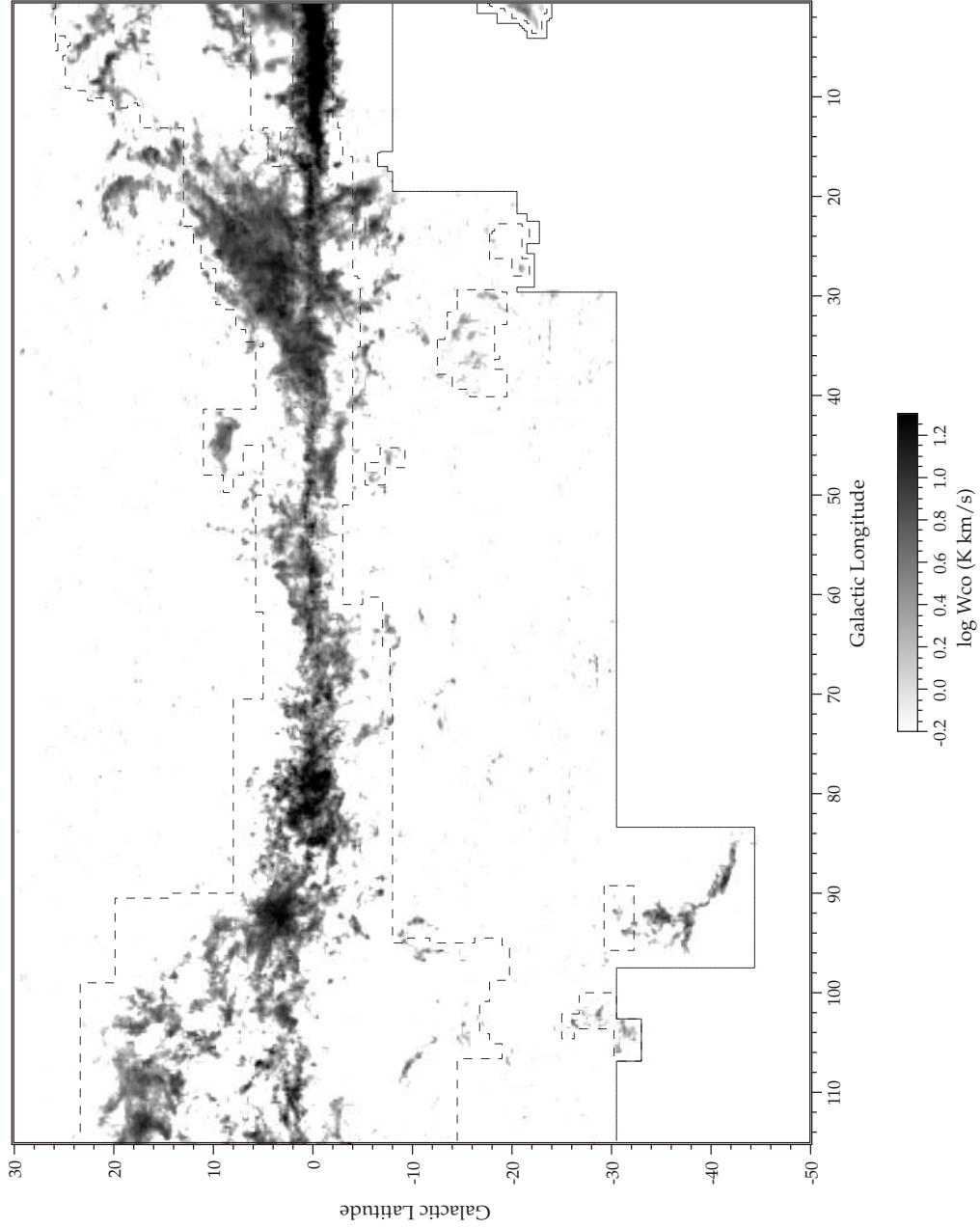


Figure 1a. A velocity-integrated CO map which combines DHT observations with better than $1/2^\circ$ resolution (within the dashed line) with the new survey here (between the dashed and solid lines). Only half of the new survey area is shown here; the other half is shown in Figure 1b. Since the new survey is still on-going, this map should be considered preliminary.

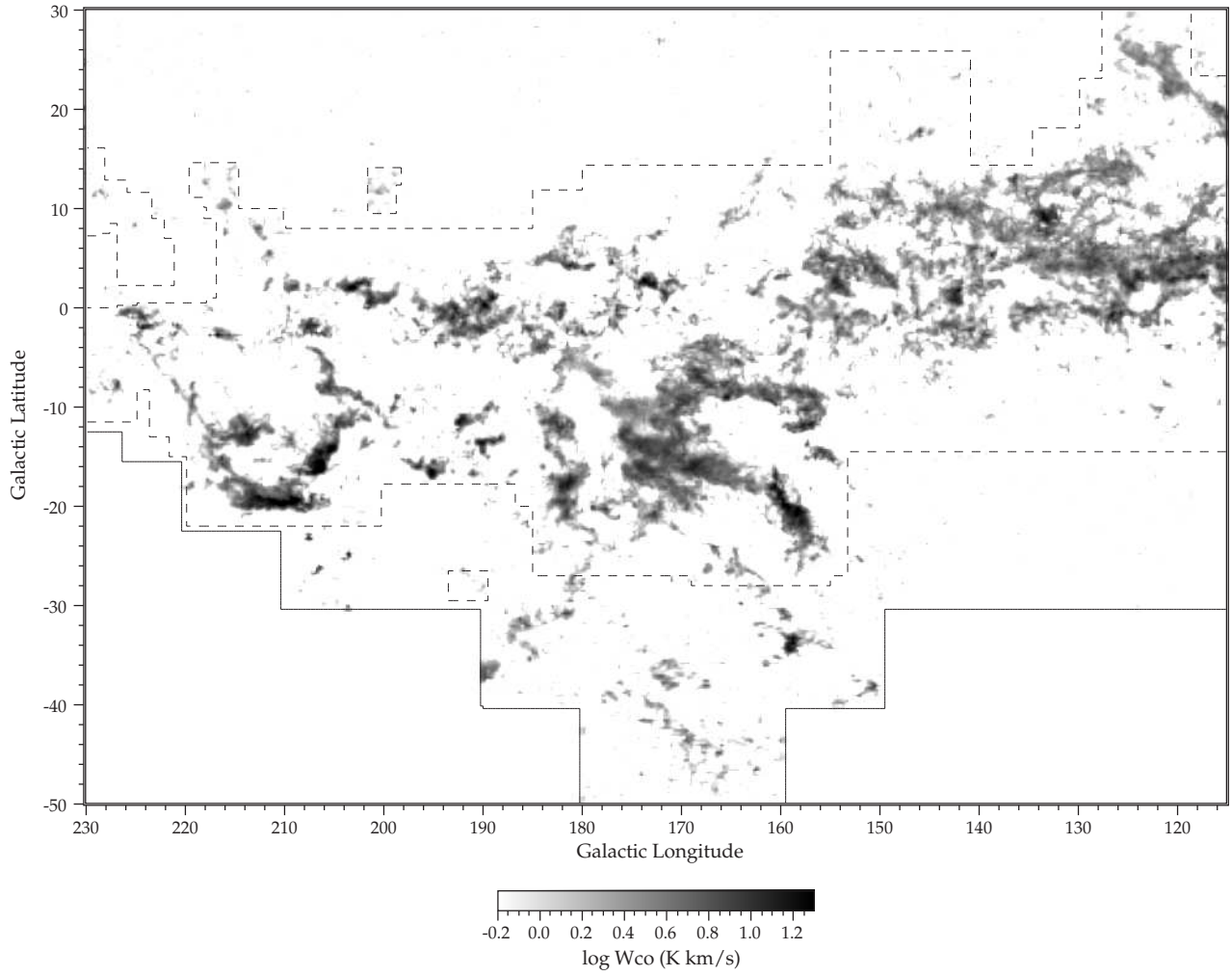


Figure 1b. A continuation of Figure 1a through the second Galactic quadrant and beyond.

we occasionally detect variations in the telluric line intensity by more than 50% in less than a day.)

3. Results at $|b| < 30^\circ$

The molecular Galaxy over the full longitude range of the present survey is shown in Figures 1*a* and 1*b*. The area mapped previously by DHT at better than $1/2^\circ$ resolution is enclosed by the dashed line, and the limits of the new survey are marked by the solid line. It is to be emphasized that the present survey is still underway, and some regions are noisier than others owing to incomplete sampling. The observations at $b < -30^\circ$ will be discussed in the next section. Here we focus on the region of the DHT map, $|b| < 30^\circ$. As predicted by DHT, only small clouds were found in the previously unobserved regions. The large foldout map published by DHT is therefore a remarkably complete inventory of molecular clouds in the Galaxy within 30° of the plane. One exception is the region of the Chamaeleon clouds, which lies in the southern sky beyond the reach of the present survey. In DHT Chamaeleon was identified as the one region where substantial CO emission might have been missed, since the sampling there was tightly confined to the three main clouds. Observations by the NANTEN telescope reported at this meeting (Mizuno et al.) do indeed show a substantial amount of CO emission in that region.

Although the new observations here add little to the DHT map, they have revealed about 68 small, isolated clouds or clouds clusters, most barely visible on the scale of Figure 1, that are apparently unrelated to large well-known molecular objects such as the Polaris Flare or the Aquila Rift. There are in addition a few dozen more tentative detections which require confirmation. Since only a few of the 68 definite detections match the high-latitude clouds cataloged by Magnani, Blitz, & Mundy (1985; hereafter MBM), it is likely that most were entirely unknown before the present work. Before finishing the survey, we will obtain fully-sampled maps of all these objects to better determine masses and internal structures. These high-latitude objects are presumably quite close, and may be the closest molecular objects in the Galaxy; they may be useful in tracing out large-scale spatial and kinematic structures such as supershells.

Even with the new clouds here, the region at $|b| = 20^\circ\text{--}30^\circ$ is so deficient in molecular gas that it is reasonable to ask whether our detection rate there is less than expected on extrapolating from the distribution in the plane. On the assumption that we are located near the center of a plane-parallel uniform distribution of molecular gas with a mean surface density of $0.87\text{ M}_\odot\text{ pc}^{-2}$ and a thickness of 87 pc (Dame et al. 1987), we calculate that the observed detection rate is indeed about a factor of 5 smaller than expected. Because much of the local molecular gas, however, is not uniformly distributed, but is concentrated in a few large clouds like those in Taurus, this deficiency is plausibly a statistical fluctuation.

4. The Taurus-South and MBM 54 Extensions

Several years ago Magnani et al. (2000) used the Northern 1.2 m telescope to survey the entire southern Galactic hemisphere at $b < -30^\circ$ and $\delta > -17^\circ$ every

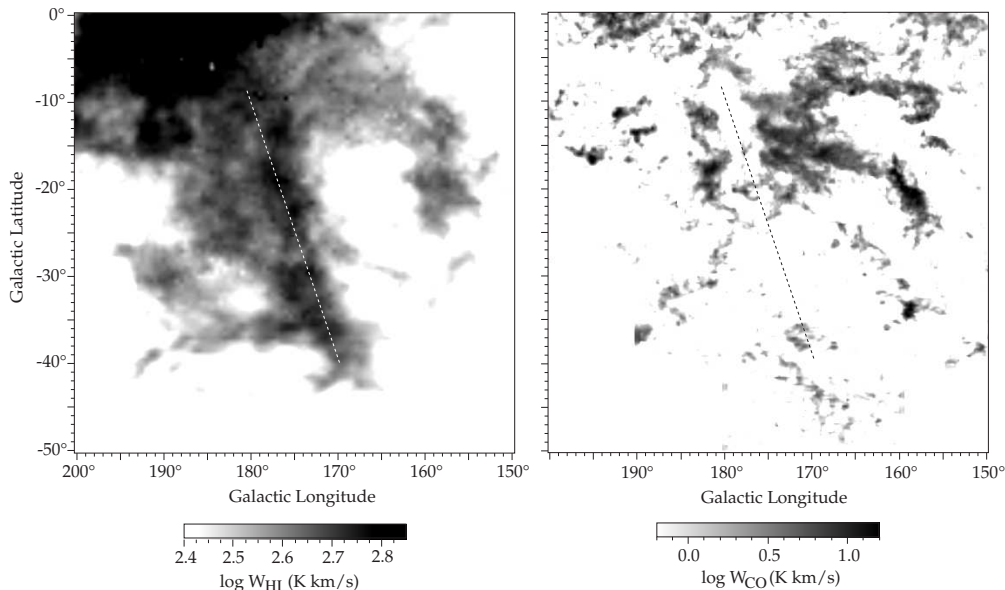


Figure 2. *Left:* 21 cm emission from the survey of Hartmann & Burton (1997), integrated from 2 to 10 km s⁻¹. The grayscale spans a relatively small range of intensities in order to emphasize the worm-like feature. *Right:* Velocity-integrated CO intensity, as in Figure 1. The region at $b < -30^\circ$ is still irregularly sampled at slightly better than $1/2^\circ$. The same sloping dashed line is plotted in both figures to aid comparison.

one degree. While the overall filling factor of CO in that region was found to be low (0.03), two regions showed a fairly large number of detections, one south of the Taurus clouds (hereafter, the Taurus-S region), the other in the vicinity of the MBM 53, 54, and 55 clouds. In the past year we have extended our survey to cover both of these regions, and as Figure 1 shows, both as suspected contain substantial amounts of molecular gas.

Our mapping of the MBM 53-55 clouds, near $l \sim 90^\circ$, was completed by E. Aguti, who has a separate contribution in this volume on these interesting objects. It was not clear from the sparse mapping in MBM that the individual clouds MBM 53, 54, and 55 were related, but Aguti's more sensitive and uniformly-sampled map shows that almost certainly they are, since they all lie within a common envelop of emission in a region otherwise nearly devoid of molecular gas. Further, as Aguti et al. show, all three clouds lie along the edge of an apparent expanding shell of H I (noted also by Gir et al. 1994). Onishi also has a contribution here describing new ¹²CO, ¹³CO and C¹⁸O observations of MBM 53-55 with the NANTEN telescope.

In the Taurus-S region, less than three of the four projected half-degree grids are now complete. It is however already clear that for a region so far from the plane, Taurus-S contains a substantial amount of molecular gas. Because of the rarity of molecular gas more than 10° from the plane in Figure 1, it seems

likely that the Taurus-S emission is related to the main Taurus-Auriga cloud complex. Magnani (1988) has similarly argued, from the distribution of IRAS emission in the region and on limited distance information, that all 8 MBM clouds in this region are probably related to the Taurus clouds.

In Taurus-S, one lane of clouds seems to extend down and to higher longitude from a vertical concentration of clouds at the edge of the Taurus clouds (near $l = 182^\circ$), while another extends down and to lower longitude from the vicinity of the Pleiades ($l = 166.5^\circ$, $b = -23.5^\circ$). The reality of these two lanes is even more apparent in the IRAS 100 micron emission. A third group of clouds lies almost directly below the Taurus clouds at an even more negative Galactic latitude (-45°); these very high-latitude clouds have a complicated velocity structure, with fragmented emission extending from -12 and $+8$ km s $^{-1}$.

As Figure 2 shows, this third group lies near the top of a rather prominent H I worm-like feature that appears to project up from the plane through a gap in the Taurus clouds near $l = 178^\circ$. The gray levels in Figure 2 have been adjusted to emphasize this large H I feature, but it is discernable even in the all-sky, all-velocity 21 cm map of Hartmann & Burton (1997; p. 53). The molecular lanes just mentioned seem to project rather symmetrically to either side of the H I feature. The complicated velocity structure of the highest-latitude clouds and their location near the top of the vertical H I structure suggest that they may not have formed there, but rather may be fragments of the Taurus clouds that were expelled to higher latitudes, along with even more atomic gas, by events close to the plane.

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